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Life cycle assessment of the Peruvian industrial anchoveta fleet: boundary setting in life cycle inventory analyses of complex and plural means of production

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Abstract
Purpose This work has two major objectives: (1) to perform an attributional life cycle assessment (LCA) of a complex mean of production, the main Peruvian fishery targeting *anchoveta* (anchovy) and (2) to assess common assumptions regarding the exclusion of items from the life cycle inventory (LCI).
Methods Data were compiled for 136 vessels of the 661 units in the fleet. The functional unit was 1 t of fresh fish delivered by a steel vessel. Our approach consisted of four steps: (1) a stratified sampling scheme based on a typology of the fleet, (2) a large and very detailed inventory on small representative samples with very limited exclusion based on conventional LCI approaches, (3) an impact assessment on this detailed LCI, followed by a boundary-refining process consisting of retention of items that contributed to the first 95 % of total impacts and (4) increasing the initial sample with a limited number of items, according to the results of (3). The life cycle impact assessment (LCIA) method mostly used was ReCiPe v1.07 associated to the ecoinvent database.
Results and discussion Some items that are usually ignored in an LCI's means of production have a significant impact. The use phase is the most important in terms of impacts (66 %), and within that phase, fuel consumption is the leading inventory item contributing to impacts (99 %). Provision of metals (with special attention to electric wiring which is often overlooked) during construction and maintenance, and of nylon for fishing nets, follows. The anchoveta fishery is shown to display the lowest fuel use intensity worldwide.
Conclusions Boundary setting is crucial to avoid underestimation of environmental impacts of complex means of production. The construction, maintenance and EOL stages of the life cycle of fishing vessels have here a substantial environmental impact. Recommendations can be made to decrease the environmental impact of the fleet.

Keywords Attributional LCA · Complex production system · Environmental impacts · Fishing vessel · Fuel use · Life cycle inventory

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1 Introduction

The whole Peruvian *anchoveta* (*Engraulis ringens*) fishery is the largest monospecific fishery[1] in the world and supports the first national industry worldwide in terms of production and exportation of fishmeal and fish oil (mostly devoted to feeds for aquaculture and animal husbandry). The fleet landed an

[1] The fishery has been considered monospecific since 2003, at least according to official statistics, although obviously minor quantities of other species are caught—mostly the longnose anchovy (*Anchoa nasus*) that are also reduced into fishmeal. Before the collapse of the sardine stock, this species and others were also landed in large quantities.

average of 6.5 million t per year in the period 2001–2010, according to statistics from the Ministry of Production of Peru (PRODUCE 2012). The fleet consists of three segments, the most productive segment being the steel-hulled industrial fishing vessels (approximately 660 units currently operating under regime Decree Law No. 25977). Catches by the steel fleet represent approximately 81 % of the total anchoveta catches (Fréon et al. 2010). Additionally, almost 690 wooden semi-industrial vessels (nicknamed “Vikingas”, operating under Law No. 26920) also target anchoveta for reduction and approximately 840 small- and medium-scale wooden vessels target mainly anchoveta, in principle for direct human consumption (PRODUCE 2012), although a large part of this third segment of the fleet is also illegally fishing for reduction (Fréon et al. 2010). There are 160 industrial reduction plants in Peru, most of them producing high protein fishmeal (PRODUCE 2012).

Industrial anchoveta fishing operations started in the 1960s and reached a captures peak in 1970 (over 12 million t, or ~20 % of the world’s catch), to decline dramatically during the 1970s and 1980s due to the combination of overexploitation, a regime shift in the ecosystem and the occurrence of very strong El Niño events in 1972 and 1982, as shown in the Electronic Supplementary Material 1. The fishery is regulated according to two main fishing areas: the north-centre area (from the border with Ecuador to 16°S) where more than 90 % of the anchoveta catches of the industrial fleet occur, and the south area (from 16°S to the border with Chile). A small part of the steel fleet moves seasonally from one area to the other.

Overcapitalisation affects the anchoveta-targeting fleets and reduction industries, which is largely a result of the existence of a semi-regulated open access system that was in place until the 2008 fishing season concluded. In 2007, the fishing fleet was estimated to be between 2.5 and 4.6 times its optimal size (Fréon et al. 2008; Paredes 2010). From January 2009 onwards, an individual vessel quota (IVQ) regime was implemented in Peru, largely to avoid the race for fishing and landing that maintained fishing overcapacity. Nonetheless, this measure resulted in a minor decommissioning of vessels and nearly no dismantling (Tveteras et al. 2011). Hence, there is interest, per se, in studying the environmental performance of this unnecessarily large fleet.

Despite the importance of this reduction fishery, no comprehensive environmental assessment of the fleet currently exists in the literature, and this is possibly due to the large size and diversity of the fleet. As underlined by Parker (2012), comprehensive life cycle assessment (LCA) of the whole Peruvian anchoveta fleet, including the steel and wooden fleets, will be useful to inform environmental assessment studies of supply chains based upon anchoveta fishmeal and fish oil worldwide, especially studies of cultured seafood products consuming high fishmeal/fish oil containing feeds. To fill this gap, we compiled and analysed a life cycle inventory (LCI) and later performed an initial LCA of the industrial anchoveta fleet, towards a future comprehensive assessment of the whole fleet, including the wooden artisanal and industrial fleets.

This issue of boundary selection during LCI is particularly crucial in attributional life cycle assessments (LCAs) of complex means of production such as large factories or fishing vessels. Typically, a vessel (or better, a fishing unit (vessel + fishing gear + crew)), is a complex object consisting of hundreds of items because it combines the complexity of a household, a transport facility and a sophisticated means of extraction. This situation generates two difficulties related to cut-off criteria during the compilation of major flows of materials and energy used in the studied process. First, as quoted by Suh et al. (2004), “many excluded processes have often never been assessed by the practitioner, and therefore, their negligibility cannot be guaranteed”. Second, the sum of impacts of processes with small individual impacts (e.g. <0.5 % of the total) can be far from negligible. The problem is further complicated when these complex units of production are numerous (plurality) and diverse. In our case study, this refers to hundreds of vessels of the industrial fleet which differ not only regarding their size but also their equipment, etc. The same could also apply to case studies related to fishmeal plants, which are also numerous and diverse, but also to many other means of industrial production, food-related or not. Here, we present and apply an approach for setting boundaries for fishing unit LCIs based on detailed inventories, to make recommendations regarding which items must be included in future purse-seiner LCIs of the same fleet or similar fleets. Published inventories of fishing vessels are limited to a few items, usually less than ten, assuming that those left out have a negligible impact, which is not always obvious (Avadí and Fréon 2013). Moreover, certain arbitrary LCI design decisions have become common practice in the LCA community in general and in the fisheries LCA community in particular, where it is very common to exclude the construction and end-of-life (EOL) phases of fishing vessels, considering them negligible.

2 Methods

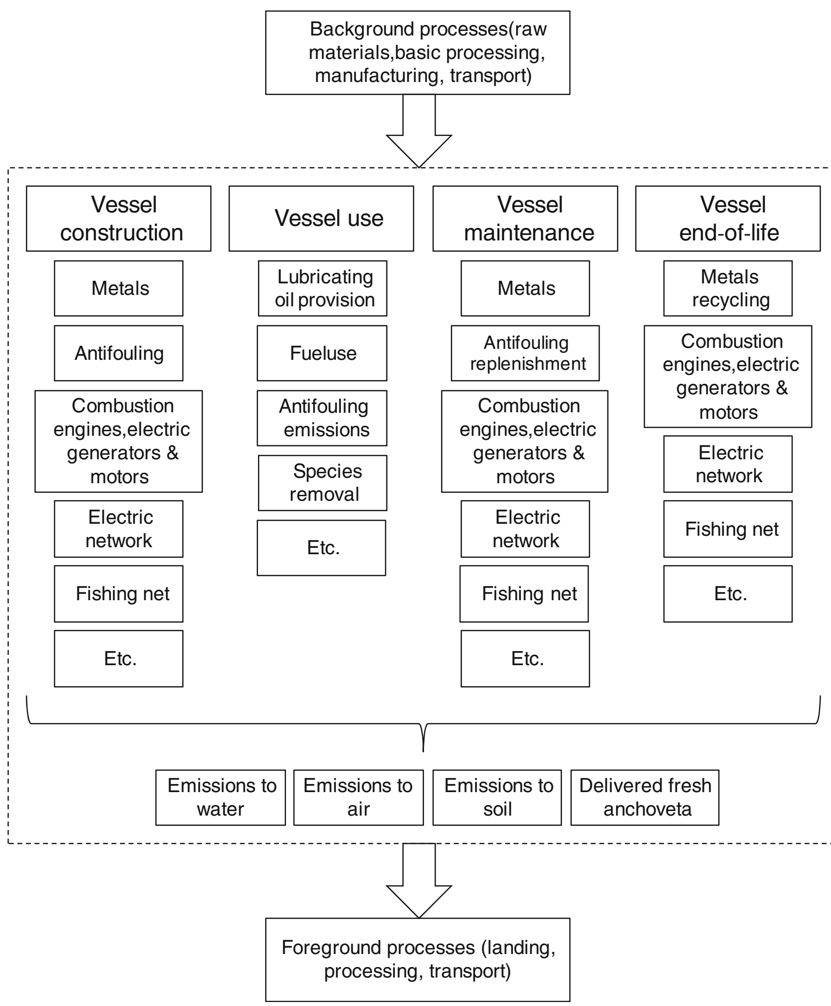
2.1 Goal and scope definition

There are two major objectives in this work: (1) to perform an attributional LCA of a complex mean of production, the Peruvian industrial fishery of steel vessels targeting anchoveta, in order to identify the major sources of environmental impacts during different stages of the life cycle and (2) to assess common assumptions regarding exclusion of items from the LCI.

The goal of the LCA is to describe the environmental impacts associated with the activity (fishing anchoveta) of the most productive segment of the fishing fleet over the life cycle of its vessels. The functional unit of choice is one averaged metric tonne (t) of fresh anchoveta caught in the north-centre (4°S–16°S) fishing zone off Peru during the period 2008–2010 and delivered to a fishing terminal by a steel industrial Peruvian purse seiner. The Peruvian industrial fishery of anchoveta does not use a pier, wharf or quay for landing anchoveta aimed at reduction into fishmeal and fish oil; vessels are discharged by pumping at a floating terminal—a.k.a. “chata”—located several hundred metres from the factory where the fish are processed. This discharge process determines the system boundary to include the fishing and exclude the landing activities (the latter can be considered part of the reduction plant). Moreover, because the study intends to assess the contribution to environmental impacts of each phase of a vessel’s life cycle, the following phases of vessels were included in the system boundary, as depicted in Fig. 1: construction, use, maintenance and decommissioning (that is EOL). Such boundaries can be defined as cradle-to-gate for the product (anchoveta) and cradle-to-grave for the vessels. We have distinguished the use and maintenance phases, which are often combined into an overall use phase (Avadí and Fréon 2013).

We have excluded from the study all items referring to fleet administration (workers, building, equipment and transportation) and on-shore processing, to delimit a perimeter strictly devoted to fishing operations. All fishing trips, successful or not, were considered in the aggregated database that we received, as were long trips made by part of the fleet when moving from South Peru (south of 16°S) to the main north-centre fishing zone. In contrast, long trips from north-centre to south and other short trips were not. The other short trips include trial trips, commuting to shipyard and commuting from one harbour to the other within the north-centre zone. Limited data available on these short trips suggest minimal impact in comparison to other trips. Crew impact is limited to emissions onboard (solid waste, wastewater) but exclude alimentation and transport. Work that is currently in progress

Fig. 1 System boundary of the industrial anchoveta fleet (only major items are depicted)



will address the remaining items of the value chain and the detailed behaviour of fishing vessels and associated fuel consumption.

Due to the diversity (size, technology) in the types of vessels, a stratification of the sampling scheme was first applied. Then, a detailed preliminary inventory was performed on a small subsample of each vessel category, partly based on ISO 14044 recommendations for the initial cut-off criteria, with deliberately low thresholds for mass and monetary value and rough estimates of environmental significance. Finally, a precise contribution of inventory items to the overall environmental impacts was calculated in the life cycle screening (LCS) and used as criteria for boundary refining in the final sampling. Because the functional unit is related to a single product, there is no need for allocation between coproducts.

The life cycle impact assessment (LCIA) method ReCiPe v1.07 (Goedkoop et al. 2009) was applied to refine the system boundary and was later used for the LCS in combination with other single issue methods available in the LCA software SimaPro v7.3 (PRé 2012) and the widely used LCI database ecoinvent v2.2 (Ecoinvent 2012). Impact categories considered were climate change, terrestrial acidification, marine eutrophication, human toxicity, photochemical oxidant formation, marine ecotoxicity, water depletion, metal depletion, fossil depletion and cumulative energy demand (CED). CED was calculated by means of the single issue LCIA method CED v. 1.08, also implemented in ecoinvent (Hischier et al. 2010).

Our boundary-refining approach accounted for the contribution of LCI items (processes or components) to impacts on several levels, as described below, with a single and arbitrary cut-off at 95 % of cumulative values of impacts, as detailed in the LCI section.

We assumed that during the initial phase of the detailed inventory, no item contributing significantly to environmental impacts according to our final criteria of boundary-refining approach would be omitted. For this reason, we set low thresholds for selection. Several assumptions regarding the inventory were made when detailed information was unavailable (e.g. estimate of the contribution of the hull weight to the total weight of the vessel, metal composition of some device, proportion of wasted oil), and these assumptions are discussed below. The major limitation of this work was the access to detailed inventory data, especially for manufactured objects that are present on most vessels, including non-fishing-specific objects.

2.2 Data sources

Data was collected for the period 2008–2011. Fishing and reduction companies were approached, as well as fishermen's associations, shipyards, governmental bodies, universities and research institutions, and experts from the anchoveta supply chains.

The authors had access to various large fishing and reduction enterprises, from which some data were obtained. Moreover, detailed inventory and operative data were obtained for the period 2008–2010 from multiple confidential and anonymous sources. Experts and observers of the anchoveta industries were also approached, and historical datasets were obtained from these sources.

Surveys were filled out at anchoveta vessel-docking sites or shipyards where vessels were meticulously inspected and their onboard documents screened, but some additional quantitative information (typically fuel consumption or weights of some items) obtained from the chief engineer or skipper was often incomplete or poor. Such incomplete datasets were complemented with data from industry providers (i.e. marine engine providers, contractors for vessel maintenance and refurbishing work, marine paint providers, shipyard operators and other supply chain players). When necessary, chemical analyses were performed.

Fleet operations data were compiled from various sources, featuring annual landings, number of fishing trips, amounts of fuel consumed, trip duration, etc. Fuel consumption figures were not available for individual trips but were provided to us annually aggregated per vessel. Actual fuel delivery to vessels is monitored from pumping facilities physically separated from the vessels by significant distances, adding small errors to the measurements.

2.3 Life cycle inventory

Our approach to the LCI consisted of four steps (Fig. 2). First, due to the high number (661) of individual purse seiners constituting the industrial steel fleet exploiting anchoveta in Peru, it was found necessary to sample this population using a stratified sampling scheme. We therefore defined a typology for this section of the fleet. Two straightforward classification options were contemplated: (a) the age of the vessel, from the assumption that more recently built vessels should benefit from more recent technology and equipment and (b) the size of the vessel with two options of easily available variables: vessel overall length or holding capacity. Classification (b) assumes that a larger vessel can carry heavier equipment regarding the three abovementioned functions of a fishing vessel (household, transport facility and a means of extraction) and that the larger vessels were built more recently, i.e. they were more modern. Vessel size expressed in holding capacity was preferred (see discussion), and the vessels were clustered into subsegments (holding capacity categories) with a class width of 80 m^3, a lower class limit of 75 m^3 and an upper limit of 875 m^3. Such clustering was found to be the best trade-off among three needs: avoiding heterogeneity within classes (80 m^3 is a conservative value), limiting unbalance in the

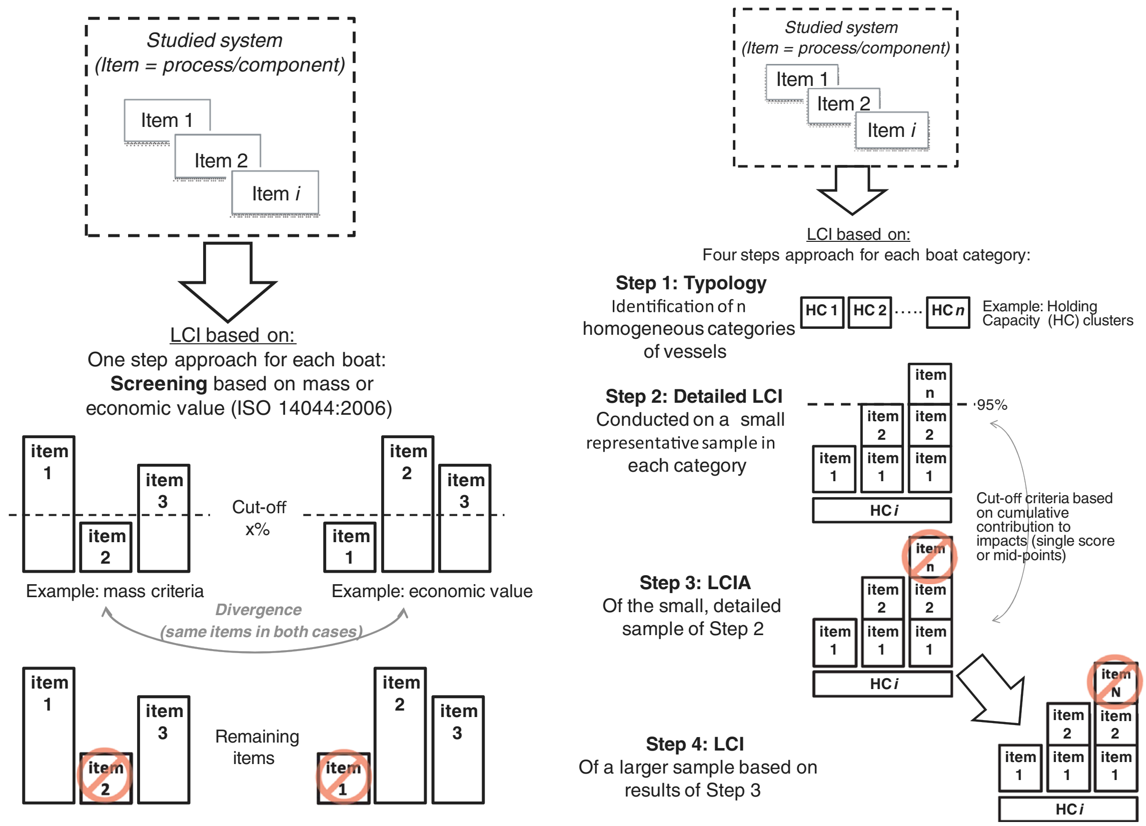


Fig. 2 The effect of reducing LCI efforts on LCIA results: comparing two boundary-refining approaches applied to the LCA of fishing vessels: *left*, ISO recommendation; *right*, the approach used in this paper. According to the size of the fleet, step 3 can be applied to all vessels or to a large representative and available sample

sampling scheme and avoiding splitting vessels belonging to the same mode within the holding capacity histogram (and often constructed during the same period, with similar design and equipment) into two adjacent classes.

The second step consisted of compilation of a large and very detailed inventory of small and representative[2] subsamples (two to four individual vessels) in each of the holding capacity categories, with very limited exclusion of obviously minor items based on conventional LCI approaches: mass (> ~0.1 % of vessel total weight), rough estimated level of environmental significance of items (expert knowledge with help of environmental impact databases when necessary), economical value (> ~US$500, that is > ~0.01 % of the vessel's total price).

During the third step, a conventional impact assessment was performed on this detailed inventory using SimaPro, followed by a boundary-refining process based on the contribution of LCI items to impacts. An empirical cut-off criterion was applied to the cumulative impacts of items ordered by decreasing order of impact, retaining all items that contributed to the sum of the first 95 % of the total (conservatively, if the last item that allows to reach the 95 % results in a cumulated contribution >95 %, it was retained). This same threshold was applied to three levels of reference: per impact category, across phases of the LCA; per phase, across impact categories and overall impact (single score). Any item contributing above any of the three levels was retained in the final LCI.

The fourth and final step consisted in increasing the initial sample in each category to a reasonable number (12 to approximately 30, when possible; Table 1), but now with a limited number of items in the LCI, according to the results obtained during step 3. Due to the difficulty of access to vessels or of obtaining detailed information once onboard, not all items of the refined LCI were sampled on each of the 136 vessels constituting the third step subset. In contrast, the most relevant inventory items (dimensions, holding capacity, age, historical captures and fuel consumption) were available not only for all inventoried vessels but also for nearly all the fleet. Dimensions (length, width, depth) and nominal holding capacity of all fishing vessels operating in Peru are published online by PRODUCE. Such data were compared with both company records and confidential and anonymous sources for validation (only a few minor discrepancies were observed). Accurate weight data were seldom available (e.g. light ship

[2] The representativeness of our sample was confirmed by the fourth coauthor of this paper, who worked for 21 years in fleet management in the largest and third largest fishing companies.

Table 1 Key inventory items for the provision of one tonne of landed *anchoveta* per holding capacity category. Some items contributed negligibly to impacts, as determined during boundary refining

Input/output	Holding capacity category	Unit	Weighted average	155–235	235–315	315–395	395–475	475–555	555–635	>635	<155	*Total*
	Basic data											
	Population	No.		185	107	131	78	35	18	9	98	*661*
	Sample fuel use	No.		64	38	88	64	29	16	4	13	*316*
	Sample other items (max)	No.		22	12	34	34	12	12	3	6	*135*
	Light ship value (average)	t		132	229	279	352	443	513			
	Holding capacity (average)	m^3		194	278	343	421	499	583			
	Construction											
I	Ballast (concrete)[a]	g	100.0	116.3	101.4	93.8	94.6	119.0	94.4			
I	Batteries (lead and sulphuric acid)[a]	g	0.6	1.3	0.9	0.7	0.5	0.5	0.4			
I	Coils (copper wire)	g	1.1	1.6	1.2	1.2	1.0	0.9	0.8			
I	Electric network (copper wire)	g	5.3	5.8	6.0	5.5	5.2	5.2	5.0			
I	Engines (metals)	g	23.0	19.8	24.4	21.2	20.8	27.6	27.3			
I	Fishing net (nylon, bronze, lead, steel, HDPE)[b]	g	84.7	120.0	94.8	86.6	88.4	72.2	67.5			
I	Hull and structure (marine steel)	g	713.4	655.5	807.2	719.7	707.7	739.1	687.2			
I	Propeller (bronze)	g	1.6	1.3	11.3	1.0	0.9	0.8	0.8			
I	Wood[a]	g	172.6	188.7	197.1	179.5	167.1	166.6	161.0			
I	Zinc[a]	g	1.0	0.7	0.5	1.2	1.2	1.1	0.7			
	Use											
O	Antifouling emissions	g	10.4	16.8	15.0	12.6	8.6	8.6	6.4			
I	Fuel use (2008–2010)	kg	15.6	14.6	15.4	15.6	16.1	16.6	14.5			
I	Lubricant oil change[a]	g	80.6	123.6	99.8	76.0	77.2	80.7	66.0			
O	Solid waste	g	202.2	203.5	203.6	203.1	202.8	203.0	202.6			
	Maintenance (replenishment, fixtures or replacements)											
I	Electric network and coils (copper wire)	g	13.3	16.6	15.2	14.2	12.7	12.3	11.4			
I	Engines (metals)	g	23.0	19.8	24.4	21.2	20.8	27.6	27.3			
I	Fishing net (nylon, bronze, lead, steel, HDPE[b])	g	762.7	1,079.6	853.2	779.3	795.7	650.1	607.9			
I	Hoses (rubber)[a]	g	7.0	14.8	10.5	7.7	6.0	5.0	4.1			
I	Hull (marine steel)	kg	1.5	1.3	1.6	1.5	1.5	1.5	1.5			
I	Hydraulic oil[a]	g	34.2	56.8	40.3	40.7	31.8	26.6	21.8			
I	Paint and antifouling	g	43.1	73.2	63.1	53.0	35.3	35.3	24.5			
I	Wood[a]	g	164.3	179.7	187.7	171.0	159.2	158.6	153.4			
	End of life (includes recycling during maintenance phase)											
O	Engines (cast iron)	g	29.9	25.7	31.7	27.6	27.1	35.8	35.4			
O	Electric network and coils (copper wire)	g	23.1	27.9	26.2	24.3	22.6	21.6	20.2			
O	Fishing net (lead)	g	122.0	175.1	137.8	124.9	126.7	103.6	96.6			
O	Fishing net (nylon)	g	542.3	767.7	606.7	554.2	565.8	462.3	432.3			
O	Hull and structure (marine steel)	kg	2.2	2.0	2.5	2.1	2.2	2.3	2.2			

Impacts from waste water and used oils disposed at sea were not characterised

Italic entries correspond to subcategories of input/output data (from "basic data" on top to "End of life (includes recycling during Maintenance phase)" at bottom of the table

[a] Inventory items *not* contributing to 95 % accumulated impacts to either the overall impacts (ReCiPe single score), within impact categories (ReCiPe midpoints), and within each life cycle phase (ReCiPe single score)

[b] High-density polyethylene

weight (LSW)). Tonnage data (gross or net) were occasionally available from various sources. Fuel consumption was compiled for most of the fleet during the period 2008–2010, and aggregated, because we did not notice a marked change in fuel use intensity from 2008 to 2009 despite the implementation of IQs at the end of 2008 (biomasses were similar in both years). We did not manage to obtain sufficient samples on both ends of the vessel size distribution (<155 m^3 and >635 m^3) and decided to omit them due to their low contribution to historical industrial landings (~5 %).

A number of assumptions, based on expert opinions, were made for data manipulation and imputation of missing values. The major ones are detailed here whereas minor ones can be found in the Electronic Supplementary Material 2:

- A total of 80 % of the LSW value is assumed to correspond, *grosso modo*, to the weight of the hull (including the frame, steel sheets, deck, etc.), while 20 % of the LSW value corresponds to the weight of structural elements (thin walls, pipes, beams, joints), propulsion and other systems (several Peruvian naval engineers, pers. comm.). The composition of electric generators and electric motors was estimated based on their weights: 43 % as steel, 33 % as copper wire (mostly coil) and 24 % as aluminium (maintenance engineer at a large fishing/processing firm, pers. comm.). These motors are estimated to be replaced every 8 years, as an average of replacement time of the different motors, pumps and generators, which range from 4 to 12 years.
- The main engine (marine diesel) was assumed to be composed as follows: 65 % cast iron, 34 % chrome steel and 1 % white metal alloys (aluminium alloy 2024, $AlCuMg_2$). This assumption is based on the work of Reenaas (2005), who analysed a Wärtsilä 6L20 engine, weighting 9.3 t (more than 60 % of engines surveyed weighed 6 t or more, and thus a similar composition could be expected). The main engine is estimated to be replaced once over the lifetime of the vessel.
- The lifetime of fishing vessels was estimated to be 40 years.
- Twelve percent of the hull (steel sheets) is changed every 2 years over the vessel's lifetime (engineers from Peruvian military and private shipyards, pers. comm.).
- In the real world, 100 % of wastewater ("black water" and "grey water") and 50 % of oil changed from the engines or hydraulic system were assumed to be spilt in the ocean, the rest being processed on land (but see below how this was modelled).
- Following Hospido and Tyedmers (2005), two thirds of the antifouling paint applied to vessels was assumed to be released into the ocean.
- The average number of fishing trips per vessel category and per year varies from 35 to 71 during the studied period (2008–2010). The single average value of 50 trips per year was retained for computing engine maintenance data because this average value is not a major source of environmental impact.

LSW is considered a good proxy for estimating the steel content of a steel-hulled vessel. Unless a stability test and record are available—which was the case for 70 vessels—it was unlikely that the LSW of vessels[3] would be known. We thus produced a number of statistical models to estimate the LSW from the holding capacity and physical dimensions of the vessels and used the most relevant model to estimate missing values of LSW:

- Histograms of candidate explanatory variables showed a close-to-normal shape, so its multivariate analysis was performed without further transformations.
- Stepwise (backward and forward) and best subsets regression tests were used to select the best among those variables to estimate LSW via a multiple regression model.
- Predicted values of LSW were computed using those explanatory variables in the most suitable linear model.

Ecoinvent 2.2 and other databases currently available in SimaPro do not include basic materials and equipment used in most industries (e.g. electric engines, specific grade steel types, etc.); thus, modelling challenges arose, and missing data had to be estimated. Moreover, various proxies had to be used for materials and processes either not represented in the databases or not characterised for Latin-American/Peruvian conditions. These proxies, whose details can be found in the Electronic Supplementary Material 2, concern the following: chemical composition of marine-grade steels antifouling paint and diesel used in Peru; metal composition of small electric engines and electric generators (<10 kW), water pumps and similar equipment; modelling of large combustion engines, lead-acid batteries, the Peruvian grid's energy mix, wood origin and cutting mode; other waterborne emissions, such as bilge oil, hydraulic oil and part of mineral oil wasted at sea, wastewater and solid waste.

These customisations were all performed within ecoinvent, retaining the original background processes.

The retained ReCiPe method is a hybrid midpoint/endpoint method, featuring 18 midpoint impact categories aggregated into three endpoint categories or areas of protection: human health, ecosystem diversity and resource availability. Three different perspectives are available in the method: individualist, hierarchist and egalitarian. Each perspective represents a set of preferences regarding assumptions and choices for,

[3] LSW values are also frequently unknown by the ship operator because most vessels were constructed several decades ago, and many of them were purchased from another company.

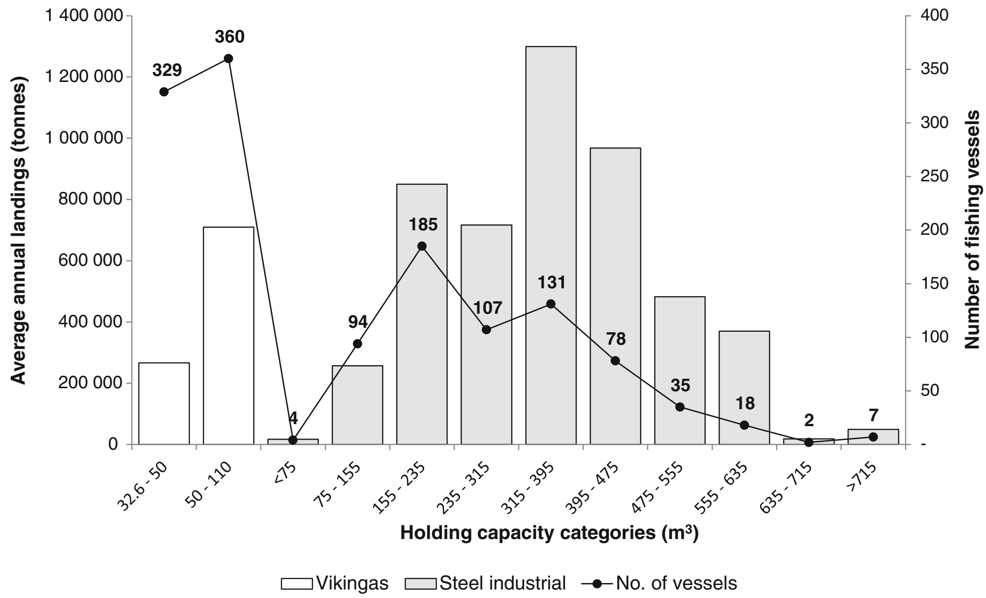


Fig. 3 Steel and wooden ("Vikinga") anchoveta fleet landings (annual average 2005–2010) and number of fishing units per holding capacity category (all vessels opertating from 2005 to 2010). Source: based upon IMARPE data

basically, timeframes used for calculation of impacts and selection of impact types. The egalitarian perspective is the most precautionary, featuring longer time horizons and impact types that are not yet fully established (Goedkoop et al. 2009). This perspective was selected to remain as conservative as possible.

The final LCAs were performed on each vessel category separately for comparison purposes, using average values within a given category. Then, an overall LCA of the industrial steel segment of the fleet was obtained by performing a weighted averaging of all vessel categories, according to landings per category.

3 Results and discussion

3.1 Inventory analysis

3.1.1 Typology of fishing units

The holding capacity categories (subsegments) representing more vessels and historical landings were found to be the 315–395 and the 395–475-m^3 segments. The smallest were found at each end of the distribution range, namely, the <155 and >635-m^3 groups (Fig. 3). The 75–155-m^3 subsegment includes a large number of vessels, yet it represents a minor contribution to overall landings in the 2005–2010 period (~4 %). The two subsegments above 635 m^3 contain only 7 vessels and represent ~1 % of the historical industrial landings. The Vikinga fleet was included in Fig. 3 for scaling purposes (this fleet represents approximately 19 % of landings)[4].

The stratification of the sampling scheme was guided by the preliminary assumption that the best typology of the fleet could be based on categories of holding capacities. This assumption was assessed a posteriori, comparing the holding capacity criteria with alternatives such as the age of the fishing vessel or its overall length because we observed covariation among the three of them. Indeed, the holding capacity, overall length and level of equipment of a vessel are roughly inversely proportional to its age. A factor analysis was first performed on the most relevant LCI items (fuel consumption and weights of grade steel, engines and antifouling paints) weighted by their contribution to the overall impact. Then, a cluster analysis was performed on the first two factors. The results showed four clear clusters that were well-structured first by holding capacity, slightly less by overall length, and poorly by age. Age was less relevant than the two vessel size indices for two reasons: (1) additional equipment on recent vessels does not form part of the list of items contributing to the first 95 % of overall impact, except for a small share of metals (additional engines and generators) and (2) age distribution is trimodal with two major modes at approximately 45 and 22 years old, and minor mode at 10, but these modes are not fully consistent with vessel size.

Linear discriminant analyses were performed to better assess the difference between a typology based on holding capacities versus a typology based on overall lengths, and to determine whether we were too conservative in using seven clusters when the a posteriori cluster analysis suggests only four. The results showed a fairly good discrimination of the seven clusters of holding capacities, despite an overlap of the confidence ellipses of the three central classes (Electronic Supplementary Material 4), but an even better discrimination of clusters based on seven clusters of overall lengths, with an

[4] Vikingas are clustered into two holding capacity categories including the official upper and lower boundaries, 32.6–50 and 50–110 m^3.

overlap of only two ellipses (Electronic Supplementary Material 5). The better performance of overall length was not expected because most of the mass of LCI items increases with volume rather than with length; however, the overall length of a vessel may better reflect its volume than does its holding capacity. Gross tonnage (GT) may be even more appropriate than overall length, but GT information was not always available to test this assumption. Another option could be to combine the three available vessel dimensions (length, width and depth) to estimate the GT as, for instance, Saetersdal et al. (1965) did.

All the above-mentioned multivariate analyses were performed on crude inventory data because these data were collected during the LCI stage. When the same analyses were performed on data per functional unit, results were much poorer, mainly because fuel consumption according to vessel size (or age) is largely optimised by fishing companies to minimise the scale effect (see below).

3.1.2 Initial detailed inventory

As expected, the initial detailed inventory resulted in the compilation of a large number of items per vessel, on the order of >40 items (Table 1 shows only the most important items). These values are largely above the number of items usually mentioned in the current literature, which is up to eight items (Avadí and Fréon 2013), although it is not always clear if a boundary-refining approach had been applied first. In any case, our boundary-refined inventory (Table 1) contains some items that were never considered in fisheries studies that are currently published, although these items belong to the items contributing to 95 % of the cumulative impact in at least one impact category. These items include provision of copper, disposal of solid waste (although not properly estimated because the fraction disposed at sea is not characterised) and impacts of paint other than antifouling releases as detailed below. The environmental impact of marine paints has often been limited to antifouling paint due to its release of toxic substances into the marine ecosystems (marine ecotoxicity). Nonetheless, other relevant impacts are freshwater eutrophication (4 %), human toxicity (5.3 %) and freshwater ecotoxicity (2.2 %) resulting from the presence of other substances in both antifouling paints and larger quantities of oil paints for superstructures and interior of the vessels, including in their excipients.

3.1.3 Data calculation

In the context of the estimation of missing LSW values, a high correlation was found between LSW and the following variables: *holding capacity* (cubic meter), *GT* (unitless index), *length* and *height* (m) but collinearity was found between *length* and *height*. Moreover, GT was also excluded from the explanatory variables due to the high number of missing values. Scatter plots of LSW versus each of the tested variables showed linearity, which justifies the use of a linear model. Finally, the best regression equation (adjusted r^2= 0.79) was found to be the following:

$$\mathrm{LSW} = -263.81 + 0.57*\mathrm{holding\quad capacity} + 43.77*\mathrm{width} \tag{1}$$

3.2 Impact assessment

3.2.1 Boundary-refining approach

The cut-off criteria discussed in the LCA ISO standard are based on mass or energy demand contribution of an item of the LCI to the overall system under study, as well as on the environmental significance (contribution to impacts) of the item (ISO 2006a; b), but these criteria are strongly criticised (e.g. Raynolds et al. (2000a, b); Suh et al. (2004)). Our approach largely follows the recommendations of ILCD (European Commission 2010) regarding cut-off criteria and combines the two suggested approaches (both seldom applied by LCA practitioners): " (a) apply the cut-off individually for each of the to-be-included impact categories […]; (b) apply the cut-off for the normalised and weighted overall environmental impact". Our results indicate that the second approach results in more items retained in the LCI, as expected (Table 2). Another difference between our approach and the ILCD approach is that we partly solved the issue of needing important approximations and extrapolations from the measured or calculated data separating the retained cut-off threshold from 100 %. This is because our initial detailed inventory on a small subsample is supposedly close enough to 100 % to be considered as exhaustive. Our boundary-refining approach deals only with the inventory of items, not the background processes.

There are practical challenges in relating specific environmental impacts to inventory items defined as new processes created in SimaPro, in order to account separately for all upstream processes (typically fuel provision and combustion given that almost every process in SimaPro consumes fuel in one way or another). The way this difficulty and related ones were overcome is presented in the Electronic Supplementary Material 6.

The major limitation of our approach is that it does not comply with one of the four criteria enunciated by Raynolds et al. (2000a) for an optimal system boundary selection: the optimal boundary selection method should "not require the quantification of environmental outputs from every unit process in the life-cycle system before system boundary selection", but it still presents the advantage of limiting inventory effort through subsampling when the means of production are plural and diverse.

Table 2 Comparison of inventory selection methods

Phase	Inventory item[a]	Mass[b] (g)	Accumulated sum (g)	Accumulated mass contribution	Item contribution to overall impacts			
					Mass method (ranking)		Impacts method (ranking)	
Use	Fuel use (2008–2010)	15,587.73	15,587.73	69.5 %	65.6 %	(1)	65.6 %	(1)
EOL	Hull and structure (marine steel)	2,195.08	17,782.81	79.2 %	9.0 %	(2)	9.0 %	(2)
Maintenance	Hull (marine steel)	1,472.35	19,255.15	85.8 %	5.9 %	(3)	5.9 %	(3)
Maintenance	Fishing net (nylon, brass, lead, steel, HDPE)	762.65	20,017.81	89.2 %	0.8 %	(5)	–	
Construction	Hull and structure (marine steel)	713.39	20,731.20	92.4 %	2.9 %	(4)	2.9 %	(5)
EOL	Fishing net (nylon)	542.33	21,273.53	94.8 %	0.6 %	(6)	–	
Use	Solid waste[c]	202.18	21,475.71	95.7 %	–		–	
Contribution to overall impacts by a mass contribution (≥95 %) method:					*84.8 %*		*83.4 %*	
Construction	Wood[c]	172.56	21,648.27	96.5 %	–		–	
Maintenance	Wood[c]	164.34	21,812.61	97.2 %	–		–	
EOL	Fishing net (lead)[c]	122.01	21,934.61	97.7 %	–		1.2 %	(9)
Construction	Ballast (concrete)[c]	100.00	22,034.62	98.2 %	–		–	
Construction	Fishing net (nylon, brass, lead, steel, HDPE)	84.74	22,119.36	98.6 %	–		–	
Use	Lubricant oil change[c]	80.55	22,199.91	98.9 %	–		–	
Maintenance	Paint and antifouling[c]	43.15	22,243.06	99.1 %	–		–	
Maintenance	Hydraulic oil[c]	34.24	22,277.30	99.3 %	–		–	
EOL	Engines (cast iron)	29.94	22,307.24	99.4 %	–		–	
EOL	Engines (chrome steel)	24.00	22,331.24	99.5 %	–		–	
EOL	Electric network and coils (copper wire)	23.12	22,354.36	99.6 %	–		2.9 %	(6)
Construction	Engines (metals)	23.03	22,377.39	99.7 %	–		–	
Maintenance	Engines (metals)	23.03	22,400.42	99.8 %	–		–	
Maintenance	Electric network and coils (copper wire)	13.27	22,413.69	99.9 %	–		1.9 %	(7)
Use	Antifouling emissions	10.40	22,424.09	99.93 %	–		1.6 %	(8)
Maintenance	Hoses (rubber)[c]	6.99	22,431.09	99.96 %	–		–	
Construction	Electric network (copper wire)	5.33	22,436.42	99.98 %	–		0.9 %	(10)
Construction	Propeller (bronze)	1.64	22,438.06	99.988 %	–		3.3 %	(4)
Construction	Coils (copper wire)	1.05	22,439.12	99.993 %	–		–	
Construction	Zinc[c]	1.04	22,440.15	99.997 %	–		–	
Construction	Batteries (lead and sulphuric acid)[c]	0.62	22,440.78	100 %	–		–	
Contribution to overall impacts by the proposed impact contribution (≥95 %) method:					*84.8 %*		*95.2 %*	

The italic entries “Contribution to overall impacts by a mass contribution (≥95%) method: 84.8% 83.4%” and “Contribution to overall impacts by the proposed impact contribution (≥95%) method: 84.8% 95.2%” correspond to a total and a subtotal of above entries, respectively

[a] Items are ranked according to their mass contribution

[b] Weighted average of all vessel categories modelled

[c] Items do not contribute to either at least 95 % of mass or of overall impacts (Table 2)

The mass approach, using the cut-off criterion of 5 %, results in selecting only 6 items from the detailed inventory versus 10 using the same criteria on per phase impacts (Table 3). As a result, the mass approach retained only 85 % of impacts instead of the expected 95 %. When extending the 5 % cut-off criterion of our approach to individual impact categories, two additional items were retained: antifouling releases and solid waste.

Based upon such outcomes, and by applying our boundary-refining approach, the inventory data collection needs were redefined, and the inventory itself was refined to include the items presented in Table 4 and summarised in Fig. 1. Conservatively, several items whose impacts were found insignificant in other studies, including specific marine-grade steels and electronic equipment, were kept in the list because some of these issues were emblematic. This list of items does

Table 3 Summary of landings and fuel consumption per holding capacity category of the six largest companies in the Peruvian *anchoveta* steel fleet (2008–2010). Source: fishing companies

Holding capacity categories	Number of vessels	Number of vessels	(A) Average annual fuel use (kg)	(B) Average annual landings (t)	Total landings (t)		(A/B) Fuel use per landed tonne (kg/t)	Category contribution to total landings	
	Whole fleet	Six companies 2008–2010	Six companies 2008–2010	Six companies 2008–2010	Whole fleet 2004–2010	Six companies 2008–2010	Six companies 2008–2010	Whole fleet 2004–2010	Six companies 2008–2010
<75	4	1	25,358	957	113,206	2,871	26.50	0.4 %	0.0 %
75–155	94	12	36,962	2,321	1,498,412	27,853	15.92	5.2 %	0.4 %
155–235	185	64	68,841	4,729	4,920,710	539,075	14.56	17.1 %	7.4 %
235–315	107	38	102,812	6,659	4,357,091	512,778	15.44	15.2 %	7.0 %
315–395	131	88	141,346	9,066	7,246,080	1,976,325	15.59	25.2 %	27.1 %
395–475	78	64	186,636	11,622	5,310,682	2,010,608	16.06	18.5 %	27.6 %
475–555	35	29	230,829	13,868	2,754,685	1,178,780	16.64	9.6 %	16.2 %
555–635	18	16	246,080	16,952	2,178,183	796,742	14.52	7.6 %	10.9 %
635–715	2	2	322,135	16,360	101,675	147,239	19.69	0.4 %	2.0 %
715–795	1	1	397,996	15,511		46,532	25.66		0.6 %
>795	6	1	382,079	18,342	275,042	55,027	20.83	1.0 %	0.8 %
Total:	*661*	*316*	*2,141,074*	*Total*:	*28,755,766*	*7,293,830*		*100 %*	*100 %*
Weighted average fuel use per landed tonne of anchoveta (kg/t):								*15.62*	*15.88*

The italic numbers represents the total

1 gal=3.7854 L, 1 L marine diesel=0.9 kg

Table 4 Analysis of impact contribution of different inventory items to one average tonnage of *anchoveta* expressed in percentages of three different references (ReCiPe endpoint): the overall impacts (single score), within impact categories, and within each life cycle phase

Inventory items	Contribution per impact category, across phases (midpoints)											
	Climate change	Ozone depletion	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication	Human toxicity	Photochemical oxidant form.	Particulate matter formation	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Ionising radiation
Fuel	86.2	94.2	93.9	27.1	86.3	34.3	96.3	90.5	71.5	31.8	9.2	57.8
Hull, structural elements, engines (steel and iron)	6.1	2.6	2.4	46.0	2.1	26.7		5.8	14.5	48.2	18.9	37.8
Electric network and coils (copper wire)				11.5		15.7			7.7	6.5	4.0	
Fishing gear, propeller (bronze)				7.1		9.8			4.7	4.0	2.5	
Paints and antifouling				4.0		5.3				2.2		
Fishing gear (nylon)	2.7				5.4					4.5		
Fishing gear (lead)						3.5						
Electronic equipment												
Antifouling releases											61.3	
Solid waste					1.3							
Sum contributions:	*95.0*	*96.8*	*96.3*	*95.8*	*95.1*	*95.3*	*96.3*	*96.3*	*98.4*	*97.2*	*95.8*	*95.6*

Inventory items	Contribution per impact category, across phases (midpoints)						Contribution per phase, across impact categories (endpoints)				Contribution to overall impacts (endpoints)
	Agricultural land occupation	Urban land occupation	Natural land transformation	Water depletion	Metal depletion	Fossil depletion	Construction	Use	Maintenance	EOL	
Fuel	92.0	63.4	98.7	41.3	1.1	85.7		99.0			*65.6*
Hull, structural elements, engines (steel and iron)	6.0	29.5		28.2	88.2	7.4	68.2		52.9	41.1	*18.2*
Electric network and coils (copper wire)		1.7			2.3		14.1		14.6	21.5	*4.9*
Fishing gear, propeller (bronze)		1.2			4.9		5.4		11.8		*3.3*
Paints and antifouling							1.0		6.7		*1.6*
Fishing gear (nylon)				25.9		3.2	2.7		6.1	31.3	*1.5*
Fishing gear (lead)							1.0		4.6	5.1	*1.2*
Electronic equipment							2.6				
Antifouling releases											
Solid waste											
Sum contributions:	*98.0*	*95.8*	*98.7*	*95.4*	*96.5*	*96.3*	*95.0*	*99.0*	*96.6*	*99.0*	*96.3*
Phase contribution to the whole life cycle:							*11.4*	*66.2*	*22.7*	*−0.4*	

All figures are expressed in %. Contributing items represent >=95 % of impacts (cumulative contribution of processes, descending order)

not contradict the more generic list in the publicly available specification (PAS-2050-2) proposed by BSI (2012) for capture fisheries, but our list is more detailed and specific to purse-seiners fisheries.

The sometimes debatable allocation of some items of the LCI to the use or maintenance phase (e.g. antifouling repainting and engine lubricating oil changes) has an impact on the relative importance of these two phases and hence on the cut-offs of these items according to their relative contribution to the corresponding phase. Nonetheless, the option of using four phases instead of three after regrouping use and maintenance presents the advantage of outlining the importance of maintenance.

3.2.2 Impact assessment of the refined inventory of the Peruvian anchoveta industrial fleet

LCI data show the benefits of scale but challenge the idea that "bigger is better", as exemplified by the behaviour of the material flow per tonne of landed anchoveta associated with increasing holding capacity not strictly decreasing for all items (e.g. engine and hull steel), as shown in Table 1.

The variability between holding capacity categories was lower than expected (limited scale effect), likely due to the optimal strategy of use of the fleet by companies that usually own all the range of categories and use them according to the abundance of the resource and its distance from the harbour. Surprisingly, some of the largest vessels impact more than the medium-sized vessels due to the difficulty they have in filling their hold during the usual duration of a trip that seldom exceeds 24–30 h. This short duration results from the absence of a refrigeration facility in most of the vessels, or from the use of this facility by equipped vessels during only short periods (pulses)[5]. Continuous use is prevented by anchoveta scales blocking the circulation system (this issue has been solved by some companies after we completed this study). Understanding and explaining the variability within and between categories of holding capacity in more detail was not possible from the dataset alone, so further data were collected (e.g. historical data of consumption, vessel monitoring system data) and analysed to explain the phenomenon. The discussion on the effects of these factors on fuel consumption variability exceeds the scope of this paper and will thus be addressed in a separate paper by the authors. A summary of landings and fuel consumption is shown in Table 5.

A comparison with other reduction fisheries is presented in Table 6, showing that the Peruvian industrial anchoveta fishery displays the lowest fuel use intensity in the world on a per landed tonne basis, a fact that could be concluded from this study. Indeed, the only other fisheries that compete with the Peruvian one are some of the North Atlantic fisheries (e.g. capelin, *Mallotus villosus*), but these fisheries operate for a very short reproductive period of high catchability. Furthermore, from the world database of fuel use intensity constructed by Tyedmers et al. (2005) and post-processing, there are no other documented industrial fisheries that display lower rates (Peter Tyedmers, Dalhousie University, pers. comm.).

The comparison of the performances of the different fleets do not seem related to the destination of landing, despite the likely competitive advantages of fleet landing for reduction (no or little preservation, bulk storage, large holding capacity allowed). Indeed, the second best performing fleet is the Basque DHC fishery of Atlantic mackerel, and there is no link between the average vessel size and fuel use intensity. It is likely that the Peruvian fleet benefits from high abundance and catchability of the Peruvian anchoveta when compared to every other species. The biomass has been fluctuating between 5 and 10 million t since the 1997/1998 strong El Niño event (Oliveros-Ramos et al. 2010), and our study period is representative of this level of abundance. Although the underlying processes determining such abundance in Peru are still debated (Fréon et al. 2009; Chavez et al. 2008; Brochier et al. 2011; Bertrand et al. 2011), an inverse correlation between increase in abundance and fuel use of the fishery has been observed in other fisheries (Ziegler and Hornborg 2013). Anchoveta fish schools remain in the upper 25 m in most fishing grounds all year long due to a shallow oxycline in coastal waters that limit their vertical habitat (Bertrand et al. 2010) and make them available to purse seiners nearly all year long. Furthermore, compared to tuna or mackerel, anchoveta are more coastal species and therefore fishing grounds are located closer to the coast, which limits fuel consumption.

The goal and definition of scope determined the initial study perimeter to be the construction, operation and disposal of anchoveta steel vessels. The LCIA produced predictable outcomes in terms of the overall results: the use phase of fishing vessels is the most important in terms of impacts, and within that phase, fuel is the leading inventory item contributing to impacts with 65.5 % of overall impacts, a value that is much higher (~90 %) in more fuel intensive fisheries (Table 6). Other relevant single sources of impacts include the provision of nylon for the fishing nets during maintenance and the provision of metals during the construction and maintenance phases (steel, brass, copper). The following contributions to overall impacts were observed per phase: construction ~11 %, use ~66 %, maintenance ~23 % and EOL −0.4 %. All of the above-mentioned results correspond to one average tonnage of anchoveta landed by the Peruvian industrial fleet exploiting the Peruvian north-central stock during the period 2008–2010. Detailed contribution to impacts is described in Table 2 (per inventory item) and Table 7 (per holding capacity category).

[5] The impact of refrigeration system is ignored because the few large vessels that have it were initially built and used for another fishery (horse-mackerel and mackerel), and most of them belong to the segment >635 m^3 which is not considered in this work.

Table 5 Life cycle impacts associated with the provision of 1 t of landed anchoveta by different vessel holding capacity categories, using all inventoried items. Based on an extended sample (135 vessels) of LCI

LCIA method	Impact category	Unit	Holding capacity categories						
			235 m^3	315 m^3	395 m^3	475 m^3	555 m^3	635 m^3	*Weighted average*
ReCiPe midpoint (excluding Marine ecotoxicity)	Climate change	kg CO_2 eq	64.64	68.34	67.79	69.41	71.51	62.96	*67.68*
	Ozone depletion	kg CFC-11 eq	7.11E-06	7.54E-06	7.55E-06	7.74E-06	8.02E-06	7.02E-06	*7.54E-06*
	Terrestrial acidification	kg SO_2 eq	0.69	0.72	0.73	0.75	0.77	0.67	*0.73*
	Freshwater eutrophication	kg P eq	7.01E-03	7.24E-03	6.68E-03	6.50E-03	6.61E-03	6.01E-03	*6.56E-03*
	Marine eutrophication	kg N eq	0.04	0.04	0.04	0.05	0.05	0.04	*0.04*
	Human toxicity	kg 1,4-DB eq	435.41	430.40	400.61	388.23	388.64	350.54	*391.15*
	Photochemical oxidant formation	kg NMVOC	0.84	0.89	0.90	0.92	0.95	0.83	*0.90*
	Particulate matter formation	kg PM10 eq	0.23	0.25	0.24	0.25	0.26	0.23	*0.24*
	Terrestrial ecotoxicity	kg 1,4-DB eq	0.03	0.03	0.03	0.03	0.03	0.02	*0.03*
	Freshwater ecotoxicity	kg 1,4-DB eq	0.25	0.27	0.25	0.25	0.25	0.23	*0.25*
	Ionising radiation	kg U235 eq	1.84	1.99	1.90	1.91	1.99	1.78	*1.89*
	Agricultural land occupation	m^2a	1.45	1.54	1.54	1.57	1.63	1.43	*1.53*
	Urban land occupation	m^2a	0.16	0.17	0.16	0.16	0.17	0.15	*0.16*
	Natural land transformation	m^2	0.07	0.07	0.07	0.07	0.08	0.07	*0.07*
	Water depletion	m^3	0.18	0.18	0.17	0.17	0.17	0.15	*0.17*
	Metal depletion	kg Fe eq	18.84	21.95	19.69	19.42	20.18	18.92	*19.60*
	Fossil depletion	kg oil eq	21.14	22.13	21.92	22.43	23.02	20.26	*21.87*
ReCiPe endpoint	Human Health	Pt (DALY)	15.29	15.91	15.38	15.44	15.79	14.05	*15.24*
	Ecosystems	Pt (species.yr)	9.89	10.12	9.73	9.71	9.87	8.79	*9.61*
	Resources	Pt ($)	1.45	1.53	1.54	1.58	1.63	1.42	*1.53*
ReciPe single score	Single Score	Pt	15.29	15.91	15.38	15.44	15.79	14.05	*15.24*
CED	Cumulative Energy Demand	MJ	1,002	1,050	1,037	1,059	1,087	958	*1,034*
Various toxicity methods	Human toxicity + ecotoxicity								
	USETox[a]	CTU	22.54	23.89	24.12	24.84	25.74	22.45	*24.11*
	Marine ecotoxicity[b]								
	ReCiPe	kg 1,4-DB eq	1,107	1,033	897	702	704	575	*787*
	CML2000 and CML 2001 infinite	kg 1,4-DB eq	22,147	22,006	20,126	18,591	18,783	16,588	*19,179*
	CML 2001 500a	kg 1,4-DB eq	654	609	530	415	416	340	*465*

[a] USETox features no characterisation factors for certain antifouling substances released in water (i.e. copper and tributyltin compounds)

[b] Differences in results among methods arise from differences in timeframes and characterisation factors

It is worth noting that PAS-2050-2 omits construction materials. Nonetheless, in fisheries that display higher rates of fuel use than the Peruvian one, the relative contribution of the construction phase to the total environmental impact is automatically lower. For the same reason, the list of non-fuel-related items or subsystems retained in the boundary-refining approach is certainly longer in our case study than it will be in other more fuel intensive fisheries when using the same approach, a statement already made by Ramos et al. (2011), who also studies a fishery with low fuel intensity.

An uncertainty analysis of the relevance of various steel types was performed by comparing and applying a Monte Carlo analysis to a vessel, considering standard *ecoinvent* steel and customised marine-grade steels ASTM A131-A and AST A36. After 300 iterations, the results show that in every impact category in ReCiPe and >95 % of the time, impacts (mostly metal depletion) will not increase significantly when specific marine steel types are modelled. Modelling specific marine grade steel types (carbon steel) in fishing units as a whole is irrelevant, despite the fact that there are dramatic differences between ASTM A131-A and AST A36. Nonetheless, one must make the distinction between chrome steels and carbon steels.

An a priori assumption was that antifouling releases would be relevant. Preliminary LCIA results proved that antifouling emissions contribute little to the environmental impacts of this fishery, despite the fact that essential metals (copper and zinc) are included in the ReCiPe egalitarian perspective we used. Marine ecotoxicity results were generated using CML

Table 6 Fuel efficiency on a per landed t basis, selected reduction fisheries

Source	kg fuel per t fish	Vessel size (m^3)[a]	Allocation	Contribution[b]	Targeted species	Fleet	Gear	Destination of landings
Vázquez-Rowe et al. (2010)	176	635	Mass	95.1 %	Horse mackerel	Galician fishery	Purse seining	DHC[c] (fresh)
Thrane (2004a)	129	395	System expansion	92.7 %	Herring	Average of Danish fisheries	trawling/purse seining	Reduction and DHC
Schau et al. (2009)	90	N/A	N/A	N/A	Small pelagics	Average of Norwegian fisheries	trawling/purse seining	Reduction
Thrane (2004a)	83	395	System expansion	89.1 %	Industrial fish (sandeel, European sprat, Norway pout)	Average of Danish fisheries	trawling	Reduction
R. Parker (pers. comm., 09.2013)	81	N/A	N/A	N/A	South Australian pilchard	Indian Ocean	purse seining	Reduction
Driscoll and Tyedmers (2010)	75	635	N/A	89.3 %	Herring	Average of North Atlantic fisheries	trawling/purse seining	Mainly for lobster bait
Parker and Tyedmers (2012)	72–172[d]	N/A	N/A	N/A	Capelin, herring, sand eels, mackerel, krill	Average of Atlantic fisheries	trawling	Reduction
Ellingsen and Aanondsen (2006)	70	395	Mass	87.3 %	Small pelagics	Average of Norwegian fisheries	trawling/purse seining	Reduction
Ramos et al. (2011)	35	395	Temporal	78.1 %	Atlantic mackerel	Basque fishery	mainly purse seining	DHC (fresh and canned)
Parker and Tyedmers (2012)	18–126[e]	N/A	N/A	N/A	Capelin, herring, menhaden, mackerel, blue whiting, sand eels, other small pelagics	Average of North Atlantic fisheries	purse seining	Reduction
Tyedmers (2004)	18–99[f]	635	N/A	85.2 %	Small pelagics	Average of North Atlantic fisheries	purse seining	Reduction
Parker and Tyedmers (2012)	17[g]	395	N/A	63.4 %	Peruvian anchoveta	Average of Peruvian industrial fishery	purse seining	Reduction
This study	15.6	395	None	60.5 %	Peruvian anchoveta	Average of Peruvian industrial fleet	purse seining	Reduction

[a] Holding capacity estimated from literature and adapted to a similar Peruvian fleet vessel size

[b] Contribution of fuel use and provision to overall impacts (ReCiPe endpoint, single score)

[c] *DHC* direct human consumption

[d] This range corresponds to 4 North Atlantic fisheries and the South Atlantic krill fishery (average: 107)

[e] This range corresponds to 8 North Atlantic fisheries (average: 66)

[f] This range corresponds to 7 reduction fisheries in the late 1990s (average: 52). Values were estimated from landings and effort data and corroborated with a limited number of specific fuel usage data (P. Tyedmers, pers. comm., 09.2013)

[g] The original source for this figure is a personal communication with a large Norwegian aquafeed producer, as mentioned in Winther et al. (2009)

methods as well (Guinée et al. 2001), as shown in Table 7, to compare this study with other studies dealing with antifouling emissions, such as those by Hospido and Tyedmers (2005). CML baseline 2000, the most used method in previous LCA studies, applies an infinite time perspective for calculating marine ecotoxicity. Thus, we observe huge differences when such results are compared against results obtained with CML 2001 for shorter time horizon (e.g. 500a) or ReCiPe (×41 and ×24 respectively), which relate more between them, whereas USETox provide values similar to CML 2000 (×1.25). Moreover, we have found that vessel LCIA results are very sensitive to the amount of copper modelled in the LCI in terms of toxicity. Because Hospido and Tyedmers (2005) did not explicitly model copper wiring (Peter Tyedmers, Dalhousie University, pers. comm..)—the main contributor to marine ecotoxicity in our model—their model assigns a higher relevance to antifouling emissions within that category. Indeed, electrical wiring is often overlooked in LCI because this item is not at sight, even in shipyards. In modern vessels, copper weight in electrical wiring expressed in 10^{th} km of cable can be roughly estimated at 1 t per 10 m of overall length of the vessel, according to consulted engineers. In the compiled LCI,

Table 7 Recommended level of detail (*ad minima*) for LCIs of purse seiners without processing plant or cooling system on board, after boundary refining and contributions observed in our case study

Item group	Attributes	Phase contribution[a]
Construction phase		
Hull	Material and mass	*11.4 %*
Structural elements	Material and mass	
Main engine	Materials and mass (cast iron, chrome steel, carbon steel, copper wire and aluminium alloy)	
Auxiliary skiff (“panga”)	Material and mass	
Electric motors, pumps, electric generators, etc.	Materials and mass (cast iron, chrome steel, carbon steel, copper wire and aluminium alloy)	
Electric system	Materials and mass of subsystems (wiring, transformers, electric generators and pumps; steel, copper)	
Propulsion system	Materials and mass (transmission, propeller)	
Fishing gear	Materials and mass (nylon, lead, brass)	
Paint and antifouling	Substances and mass (active substances, excipients)	
Batteries	Material and mass (lead, sulphuric acid, glass, etc.)	
Ballast	Material and mass	
Use phase		
Fuel	Mass	*66.2 %*
Solid waste (disposed at sea)	Mass	
Wastewater (disposed at sea)	Volume, BOD/COD	
Lubricant oil (disposed at sea)	Mass	
Antifouling releases	Mass	
Catches and discards of target and non-target species[b]	Masses and by-catch/discards characterisation	
Maintenance phase		
Paint and antifouling	Frequency and mass	*22.7 %*
Fishing gear	Mass	
Hull fixings	Materials (steel, wood) and mass	
Engine replacement	Frequency	
Electric motors, pumps, electric generators, etc.; replacement	Frequency and mass	
Batteries replacement	Frequency and mass	
End-of-Life phase		
Not relevant (vessel elements recycled, namely steel, copper, nylon, lead, electronics, oils, wood and paints)		*−0.4 %*

[a] Contribution to overall impacts in the Peruvian steel fleet, according to impact assessment method ReCiPe endpoint (single score)

[b] Catches and discard data should be also compiled, to compute species removal impact categories not currently formalised in LCA practice

copper figures are less than that ratio, due to the age of the fleet.

Wood use, despite the fact that this material comes from the primary forest in Peru and is used in large quantities (e.g. 84 t over the life cycle of a vessel in the 395–475-m^3 category), also contributes negligibly, which was unexpected. This negligible contribution is due to a much higher contribution of soybean oil (as constituency of the diesel 2/biodiesel mixture used in Peru) to impact the category natural land transformation and to the fact that we consider selective extraction, excluding clear cutting.

Ongoing studies of cultured seafood products consuming feeds rich in fishmeal and fish oil from Peru should benefit from the characterisation results of the present study. LCA studies on other purse-seiners fisheries should benefit from this work by limiting the relevant items to be included in their inventory and, at the same time, including others that are of importance but often overlooked. This study also allows some recommendations to be made to the Peruvian fishing sector, as summarised below.

4 Conclusions and recommendations

Collecting inventory data based on our boundary-refining approach of assessing contributions to impacts at various levels should allow future LCA studies of purse-seining fleets to fully assess the environmental performance of these fleets.

It became obvious that the construction, maintenance and EOL stages of the life cycle of fishing vessels have a substantial environmental impact and should not be ignored in the LCI, although the use stage remains by far the most important source of environmental impact. The following items (some of them belonging to the use stage) are too often missing in fishing vessel inventories: metals other than cast iron, lubricating oil disposed at sea, nylon, electronic equipment, copper wire from the electrical system and generators, etc. (Avadí and Fréon 2013), and some of them might be relevant in specific cases. The maintenance phase, especially in common cases like the Peruvian anchoveta fleet where large volumes of materials are replaced over the vessel life cycle, is particularly sensitive to the level of detail in characterisations (e.g. certain varieties of steel such as chrome steel) and replenishment/replacement frequency. The importance of these non-use phases is exacerbated by the relatively low level of the fuel use intensity when compared to other fisheries.

We claim that the results of our study can be generalised for purse-seiner LCA studies in general (at least those without processing plant or cooling system on board) and propose as sufficient and efficient the level of detail shown in Table 4. Catches and discarded data should also be compiled to compute species removal impact categories not currently formalised in LCA practice.

The Peruvian steel anchoveta fleet is shown to display the lowest fuel use intensity worldwide, largely due to the great abundance and catchability (including availability and accessibility) of the targeted stock. This first LCA (and a comprehensive LCA of the entire anchoveta fleet, which is in progress) contributes to the understanding of the environmental pressures exerted by this important fishery. It will need to be updated when a strong El Niño event will occur and modify the levels of abundance and catchability of the stock, hence the fuel use intensity of the fleet.

This study allows for environmental recommendations. Although the fleet is the least fuel intensive, fuel production and use remains the most contributing impact and fuel use intensity can be improved. The fleet is ageing and only some vessels benefit from the latest technological advances that allow energy saving either directly (e.g. electronic fuel injection engines, bulbous bow) or indirectly through yield increase (e.g. last generation of sonar and echosounder, navigation and communication means). A work in progress will detail actions aimed at decreasing fuel use. Hull construction and maintenance is the second item most contributing to environmental impacts. Alternative modern materials of construction exist and are used in other fisheries but only a consequential LCA could determine whether or not their environmental performance is better than steel. A traditional construction material, wood, is used in Peru by the semi-industrial fleet and a work in progress is comparing its benefit to steel's. Electrical network comes third in the list of the most impacting items due to the use of copper, but as far as we know there is not yet an alternative material available at industrial scale in the market. Nonetheless, and despite the increasing number of electric connections on-board modern fishing vessels, savings can result from an optimised wiring (naval electricity engineer, pers. comm.). The fishing net, another impacting item in the construction and maintenance phase, can also benefit from improvement of related impact, in particular through modern manipulation equipment that increase its life span. A different type of improvement can come from the recent and coming generations of antifouling paints which are less toxic than former ones. Their use must be encouraged, in particular those acting on the interference with the settlement and attachment mechanisms which are the most promising environmentally benign option (Yebra et al. 2004). Last but not the least, a further reduction of the large overcapacity of the fleet is desirable in order to decrease its environmental impact through a decrease of the non-use phases of the life cycle.

Therefore, there is room for decreasing the environmental impact of this fishery (and others), and the Peruvian government has already taken some regulating measures in the right direction (e.g. electronic fuel injection engine, antifouling paint regulation, implementation of IVQs) that need to be enforced or improved, while others must be implemented or at least evaluated.

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References

Avadi A, Fréon P (2013) Life cycle assessment of fisheries: a review for fisheries scientists and managers. Fish Res 143:21–38

Bertrand A, Ballon M, Chaigneau A (2010) Acoustic observation of living organisms reveals the upper limit of the oxygen minimum zone. PLoS ONE 5(4):e10330

Bertrand A, Chaigneau A, Peraltilla S et al (2011) Oxygen: a fundamental property regulating pelagic ecosystem structure in the coastal southeastern tropical Pacific. PloS one 6:e29558

Brochier T, Lett C, Fréon P (2011) Investigating the “northern Humboldt paradox” from model comparisons of small pelagic fish reproductive strategies in eastern boundary upwelling ecosystems. Fish and Fish 12:94–109

BSI (2012) Publicly Available Specification (PAS) 2050–2:2012 Assessment of life cycle greenhouse emissions. Supplementary requirements for the application of PAS 2050:2011 to seafood and other aquatic food products. British Standards Institution, London.

Chavez F, Bertrand A, Guevara-Carrasco R, Soler P, Csirke J (2008) Editorial: The Northern Humboldt current system: brief history, present status and a view towards the future. In: Werner F, Lough G, Bertrand A, Guevara-carrasco R, Soler P, Csirke J, & Chavez FP (eds) The Northern Humboldt current system: ocean dynamics, ecosystem processes, and fisheries. Progr Oceanogr 79:95–412

Driscoll J, Tyedmers P (2010) Fuel use and greenhouse gas emission implications of fisheries management: the case of the New England Atlantic herring fishery. Mar Policy 34(3):353–359

Ecoinvent (2012) The ecoinvent centre portal, http://www.ecoinvent.ch/. Accessed 04 Oct 2013

Ellingsen H, Aanondsen S (2006) Environmental impacts of wild caught cod and farmed salmon—a comparison with chicken. Int J Life Cycle Assess 11(1):60–65

European Commission (2010) International Reference Life Cycle Data System (ILCD) handbook: general guide for life cycle assessment—Provisions and action steps. First edition March 2010, EUR 24708 EN, Luxembourg. European Commission-Joint Research Centre-Institute for Environment and Sustainability. Luxembourg, Publications Office of the European Union.

Fréon P, Bouchon M, Mullon C, Garcia C, Niquen M (2008) Interdecadal variability of anchoveta abundance and overcapacity of the fishery in Peru. Progr Oceanogr 79(2–4):401–412

Fréon P, Barange M, Arístegui J (2009) Eastern boundary upwelling ecosystems: integrative and comparative approaches, an introduction. Progr Oceanogr 83(1–4):1–14

Fréon P, Bouchon M, Domalain G, Estrella C, Iriarte F, Lazard J, Legendre M et al. (2010) Impacts of the Peruvian anchoveta supply chains: from wild fish in the water to protein on the plate. GLOBEC Int Newsl (April): 27–31.

Goedkoop M, Heijungs R, Huijbregts M, Schryver AD, Struijs J, Zelm RV (2009) ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: characterisation, ministry of housing, spatial planning and environment (VROM). http://www.lcia-recipe.net/. Accessed 04 Oct 2013

Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, Koning A de, Oers L van, Wegener Sleeswijk A, Suh S, Udo de Haes HA, Bruijn H de, Duin R van, Huijbregts MAJ (2001) Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: guide. IIb: operational annex. III: scientific background. Kluwer Academic Publishers, ISBN 1-4020-0228-9, Dordrecht, 2002, 692 pp.

Hischier R, Weidema B, Althaus H-jörg, Bauer C, Doka G, Dones R, Frischknecht R et al. (2010) Implementation of life cycle impact assessment methods. Ecoinvent report No. 3 Dübendorf.

Hospido A, Tyedmers P (2005) Life cycle environmental impacts of Spanish tuna fisheries. Fish Res 76(2):174–186

International Organisation for Standardisation (ISO) (2006a) Environmental management-life cycle assessment—principles and framework. EN ISO 14040

International Organisation for Standardisation (ISO) (2006b) Environmental management-life cycle assessment-requirements and guidelines. EN ISO 14044

Oliveros-Ramos R, Guevara-Carrasco R, Simmonds J, Csirke J, Gerlotto F, Pena C, Tam J (2010) Modelo de evaluación integrada del stock norte-centro de la anchoveta peruana *Engraulis ringens* Jenyns. Bol Inst Mar Perú 25:49–55

Paredes C (2010) Reformando el Sector de la Anchoveta Peruana Progreso Reciente y Desafíos Futuros (Reforming the Peruvian anchovy sector: recent progress and future challenges). Instituto del Perú - Cuadernos de Investigación (pp 1–23). http://www.institutodelperu.org.pe/descargas/Publicaciones/DelInstitutodelPeru/DOC/contenido_carlos_paredes_-_reforma_de_la_presqueria_anchoveta_peru.pdf. Accessed 04 Oct 2013

Parker R (2012) Review of life cycle assessment research on products derived from fisheries and aquaculture: a report for seafish as part of the collective action to address greenhouse gas emissions in seafood. Final report. Sea fish industry authority, Edinburgh. http://www.seafish.org/media/583639/seafish_lca_review_report_final.pdf. Accessed 04 Oct 2013

Parker R, Tyedmers P (2012) Life cycle environmental impacts of three products derived from wild-caught Antarctic krill (*Euphausia superba*). Envir Sci Tech 46:4958–4965

PRé (2012) SimaPro by Pré Consultants. http://www.pre-sustainability.com/content/simapro-lca-software/. Accessed 04 Oct 2013

PRODUCE (2012) Ministry of production of Peru, statistics section. http://www.produce.gob.pe/. Accessed 04 Oct 2013

Ramos S, Vázquez-Rowe I, Artetxe I, Moreira MT, Feijoo G, Zufía J (2011) Environmental assessment of the Atlantic mackerel (*Scomber scombrus*) season in the Basque Country. Increasing the timeline delimitation in fishery LCA studies. Int J Life Cycle Assess 16(7):599–610

Raynolds M, Fraser R, Checkel D (2000a) The relative mass-energy-economic (RMEE) method for system boundary selection. Part 1: a means to systematically and quantitatively select LCA boundaries. Int J Life Cycle Assess 5(1):37–46

Raynolds M, Fraser R, Checkel D (2000b) The relative mass-energy-economic (RMEE) method for system boundary selection. Part 2: selecting the boundary cut-off parameter (Z_{RMEE}) and its relationship to overall uncertainty. Int J Life Cycle Assess 5(2):96–104

Reenaas M (2005) Solide oxide fuel cell combined with gas turbine versus diesel engine as auxiliary power producing unit onboard a passenger ferry: a comparative life cycle assessment and life cycle

cost assessment. Masters Dissertation, Norwegian University of Science and Technology

Saetersda G, Tsukayama Alegre B (1965) Fluctuations in the apparent abundance of the anchovy stock in the 1959–1962. Bol Inst Mar Peru 2:33–104

Schau E, Ellingsen H, Endal A, Aanondsen S (2009) Energy consumption in the Norwegian fisheries. J Clean Prod 17(3):325–334

Suh S, Lenzen M, Treloar G, Hondo H (2004) System boundary selection in life-cycle inventories using hybrid approaches. Envir Sci Tech 38(3):657–664

Thrane M (2004) Environmental impacts from Danish fish products—hot spots and environmental policies. PhD Dissertation, Aalborg University, Denmark

Tveteras S, Paredes CE, Peña-Torres J (2011) Individual fishing quotas in Peru: stopping the race for anchovies. Mar Res Econ 26:225–232

Tyedmers P, Watson R, Pauly D (2005) Fueling global fishing fleets. Ambio 34(8):635–638

Vázquez-Rowe I, Moreira MT, Feijoo G (2010) Life cycle assessment of horse mackerel fisheries in Galicia (NW Spain). Comparative analysis of two major fishing methods. Fish Res 106(3):517–527

Winther U, Ziegler F, Hognes ES, Emanuelsson A, Sund V, Ellingsen H (2009). Carbon footprint and energy use of Norwegian seafood products. SINTEF Fisheries and Aquaculture (p 89). http://www.sintef.no/upload/Fiskeri_og_havbruk/Fiskeriteknologi/Filer%20fra%20Erik%20Skontorp%20Hognes/Carbon%20footprint%20and%20energy%20use%20of%20Norwegian%20seafood%20products%20-%20Final%20report%20-%2004_12_09.pdf. Accessed 04 Oct 2013

Yebra DM, Kiil S, Dam-Johansen K (2004) Antifouling technology—past, present and future steps towards efficient and environmentally friendly antifouling coatings. Progr Organic Coatings 50:75–104

Ziegler F, Hornborg S (2013) Stock size matters more than vessel size: the fuel efficiency of Swedish demersal trawl fisheries 2002–2010. Mar Pol 44:72–81